BETA-BEAMS USING THE TEVATRON

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NB. Large parts of this talk comes from the CERN beta beam working group and its web site:
http://cern.ch/beta-beam
(especially M. Benedikts NuFact04 talk)

Outline

- Intro to beta-beams and the CERN/EU study
  - The baseline scenario, ion choice, main parameters
  - Ion production and acceleration
  - Decay ring design issues
- Physics reach
  - The case for higher gamma
- Beta beams at Fermilab using the Tevatron?
  - 1TeV decay ring on the Fermilab site.
- Conclusions

Introduction to Beta-beams

- Beta-beam proposal by Piero Zucchelli:
  - *A novel concept for a neutrino factory: the beta-beam*, Phys. Let. B, 532 (2002) 166-172.

- AIM: production of pure beams of electron neutrinos (or antineutrinos) from the beta decay of radioactive ions, circulating in a high energy decay ring (γ~100)

- The CERN baseline scenario
  - Avoid anything that requires a “technology jump” which would cost time and money (and be risky)
  - Make use of a maximum of the existing infrastructure

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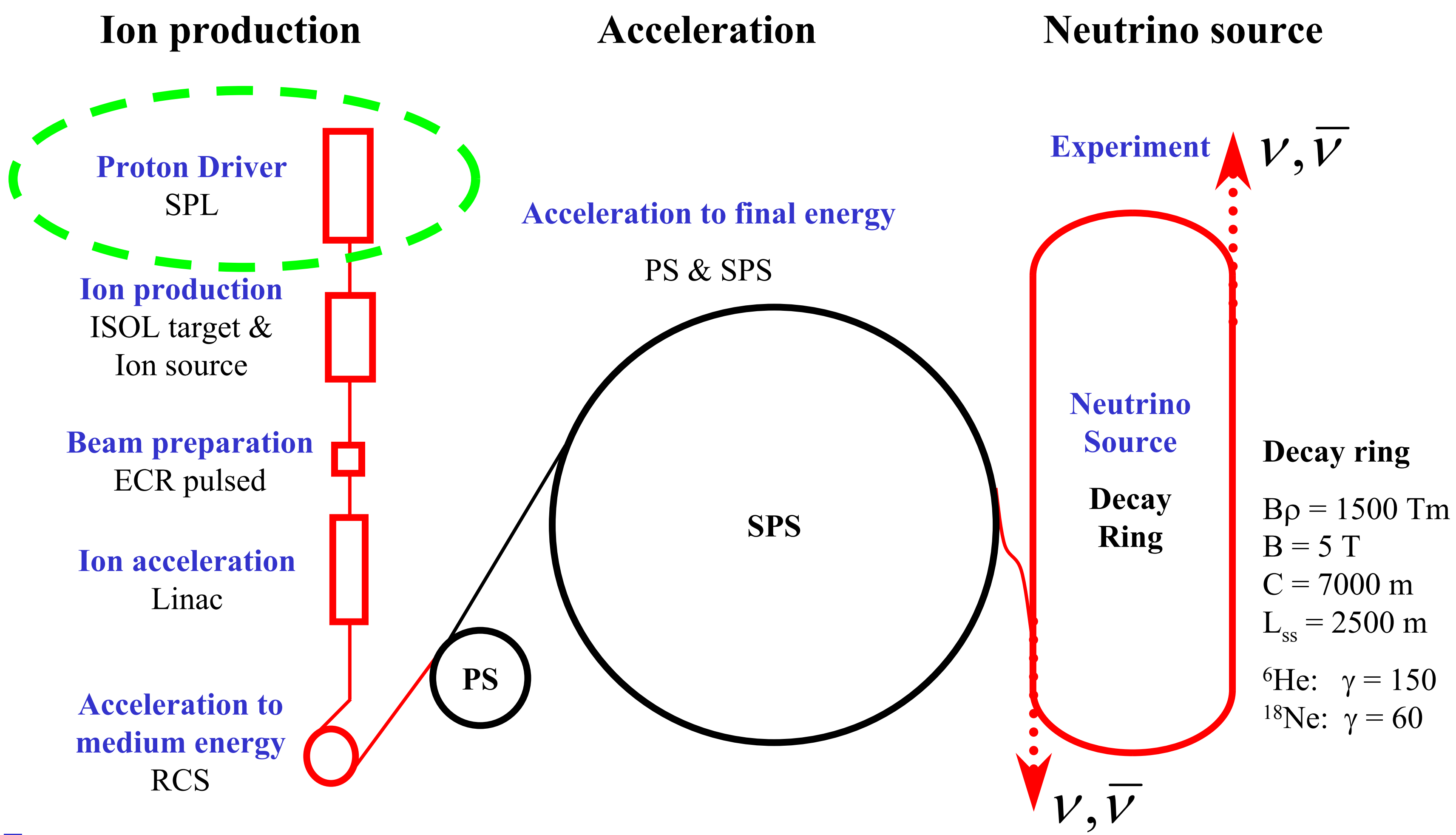
Beta-beam baseline design



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Main parameters (1)

- Ion choice
  - Possibility to produce reasonable amounts of ions
  - Noble gases preferred - simple diffusion out of target, gas phase at room temperature
  - Not too short half-life to get reasonable intensities
  - Not too long half-life as otherwise no decay at high energy
  - Avoid potentially dangerous and long-lived decay products

- Best compromise
  - ^{6}Helium^{2+} to produce antineutrinos:

$$ {}^{6}_{2}He \rightarrow {}^{6}_{3}Li\, e^{-}\, \overline{\nu} $$

$$ \text{Average } E_{cms} = 1.937 \text{ MeV} $$

  - ^{18}Neon^{10+} to produce neutrinos:

$$ {}^{18}_{10}Ne \rightarrow {}^{18}_{9}Fe\, e^{+}\, \nu $$

$$ \text{Average } E_{cms} = 1.86 \text{ MeV} $$

slide from M. Benedikt

Main parameters (2)

- Target values in the decay ring

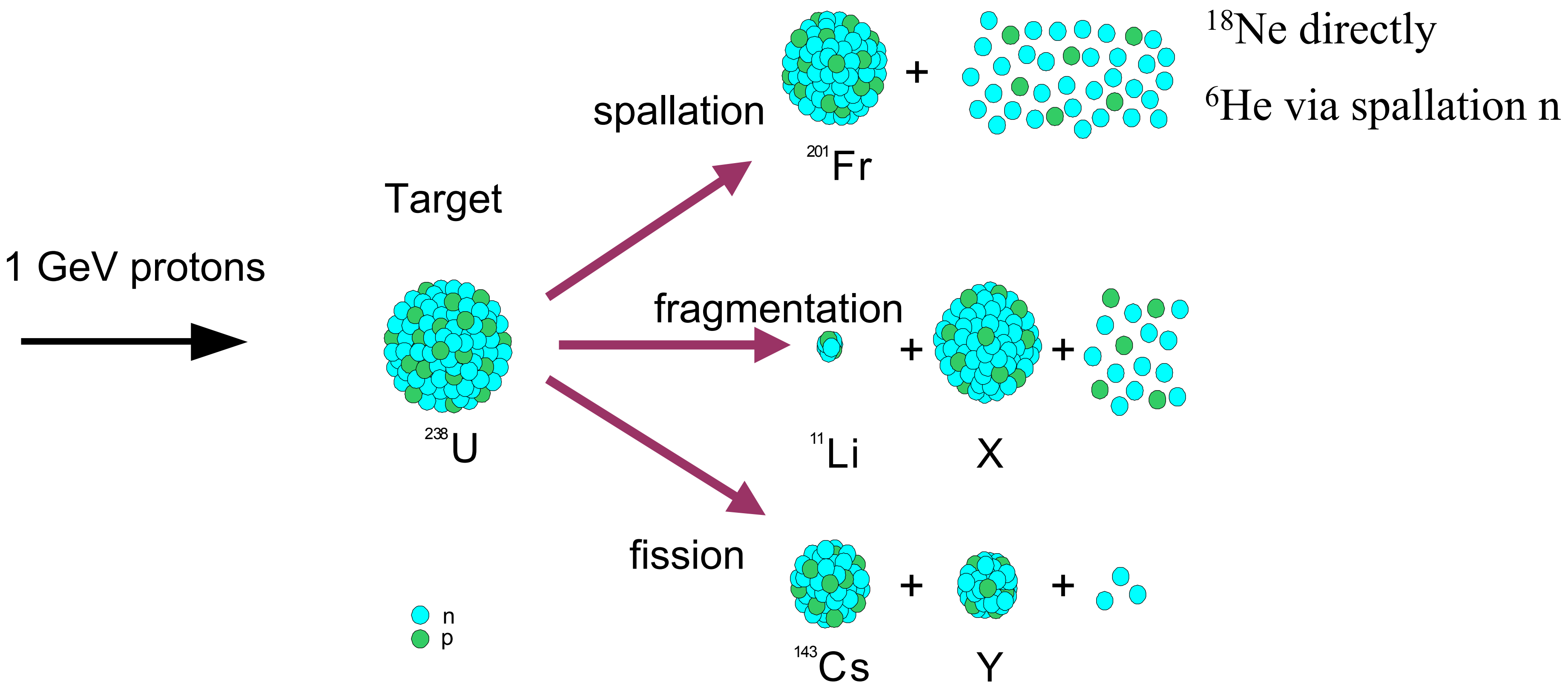
^{6}Helium^{2+}		^{18}Neon^{10+} (single target)	
– Intensity (av.):	$1.0\text{x}10^{14}$ ions	– Intensity (av.):	$4.5\text{x}10^{12}$ ions
– Energy:	139 GeV/u	– Energy:	55 GeV/u
– Rel. gamma:	150	– Rel. gamma:	60
– Rigidity:	1500 Tm	– Rigidity:	335 Tm

- The neutrino beam at the experiment has the "time stamp" of the circulating beam in the decay ring.
- The beam has to be concentrated in as few and as short bunches as possible to maximize the peak number of ions/nanosecond (background suppression).
- Aim for a duty factor of 10^{-4} -> this is a major design challenge!

slide from M. Benedikt

Ion production - ISOL method

- Isotope Separation OnLine method.
- Few GeV proton beam onto fixed target.



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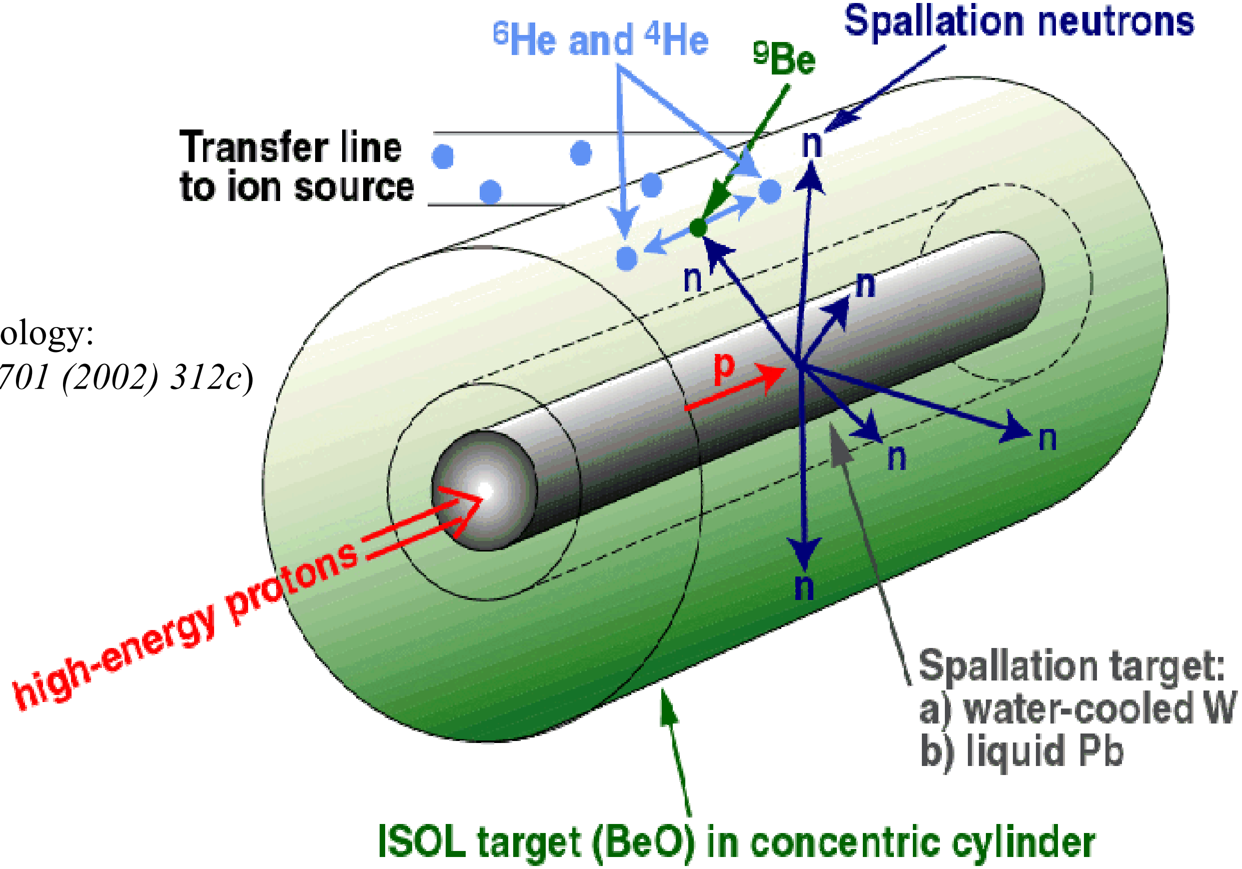
^{6}He production from ^{9}Be(n,α)

Converter technology:
(*J. Nolen, NPA 701 (2002) 312c*)



- Converter technology preferred to direct irradiation (heat transfer and efficient cooling allows higher power compared to insulating BeO).
- ^{6}He production rate is ~2x10^{13} ions/s (dc) for ~200 kW on target.

slide from M. Benedikt

^{18}Ne production

- Spallation of close-by target nuclides: ^{18}Ne from MgO:
  - $^{24}Mg^{12}$ (p, p_3 n_4) $^{18}Ne^{10}$
  - Direct target: no converter technology can be used, the beam hits directly the oxide target.
  - Production rate for ^{18}Ne is ~ 1×10^{12} ions/s (200 kW dc proton beam at a few GeV beam energy).
  - ^{19}Ne can be produced with one order of magnitude higher intensity but the half life is 17 seconds!

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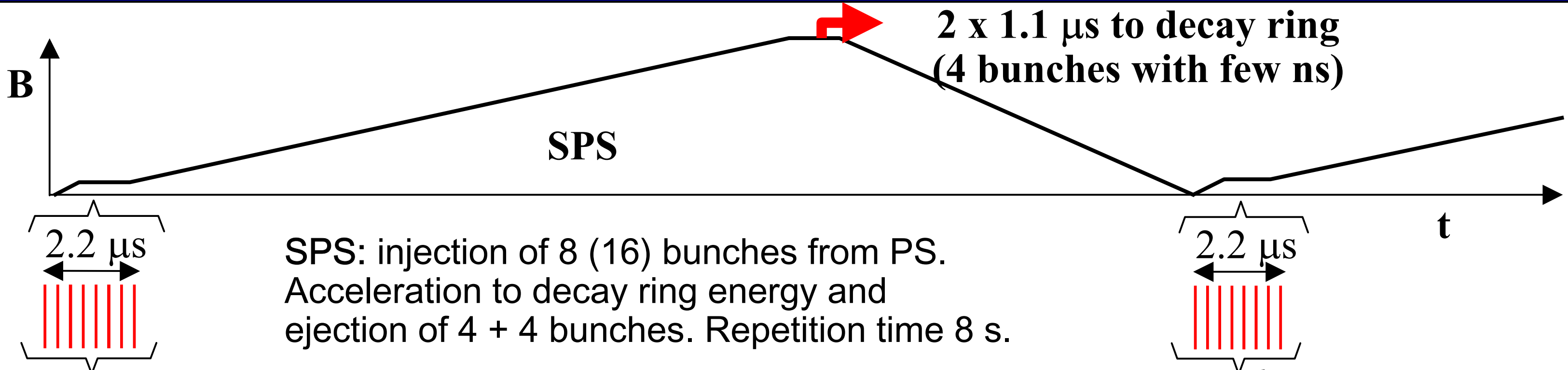
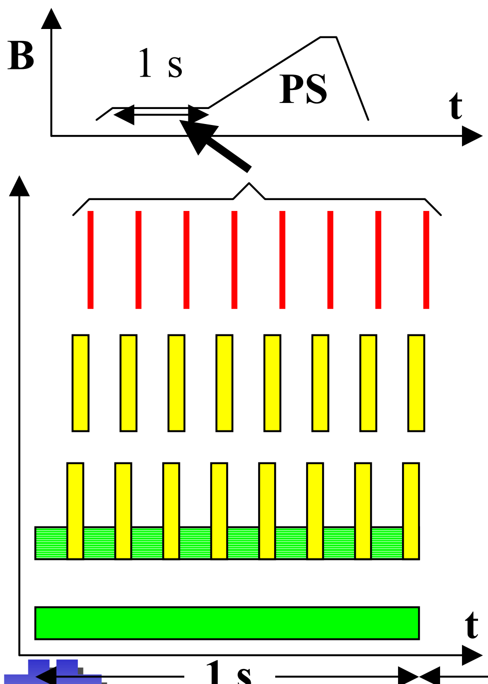
From dc ions to very short bunches



SPS: injection of 8 (16) bunches from PS. Acceleration to decay ring energy and ejection of 4 + 4 bunches. Repetition time 8 s.



PS: 1s flat bottom with 8 (16) injections. Acceleration in ~1s to top PS energy

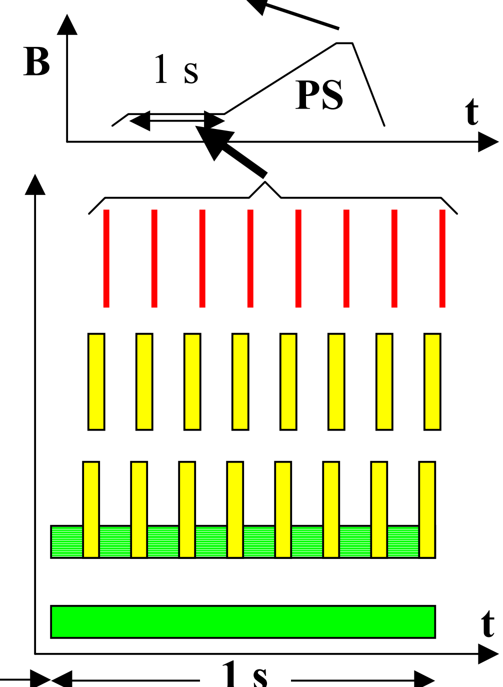
RCS: further bunching to ~100 ns Acceleration to ~300 MeV/u. 8 (16) repetitions over 1s.

Post accelerator linac: acceleration to ~100 MeV/u. 8 (16) repetitions over 1s.

60 GHz ECR: accumulation for 1/8 (1/16) s ejection of fully stripped ~20μs pulse. 16 batches during 1s.

Target: dc production during 1 s.

7 s



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Decay ring design aspects

- The ions have to be concentrated in very few very short bunches.
  - Suppression of atmospheric background via time structure.
- There is an absolute need for stacking in the decay ring.
  - Not enough flux from source and injection chain.
  - Life time is an order of magnitude larger than injector cycling (120 s as compared to 8 s SPS cycling).
  - We need to stack at least over 10 to 15 injector cycles.
- Cooling is not an option for the stacking process:
  - Electron cooling is excluded because of the high electron beam energy and in any case far too long cooling times.
  - Stochastic cooling is excluded by the high bunch intensities.
- Stacking without cooling creates “conflicts” with Liouville.

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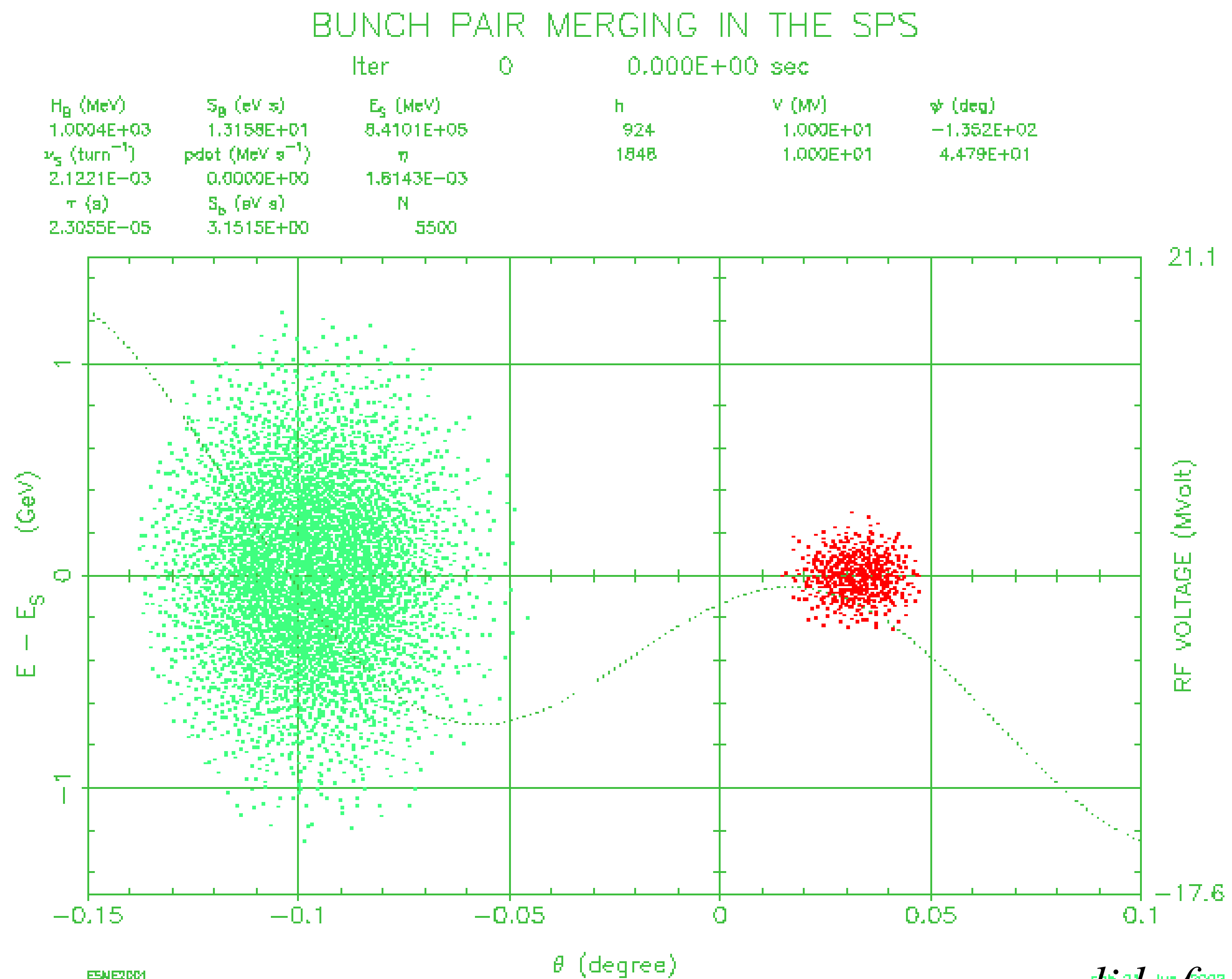
Full scale simulation for SPS



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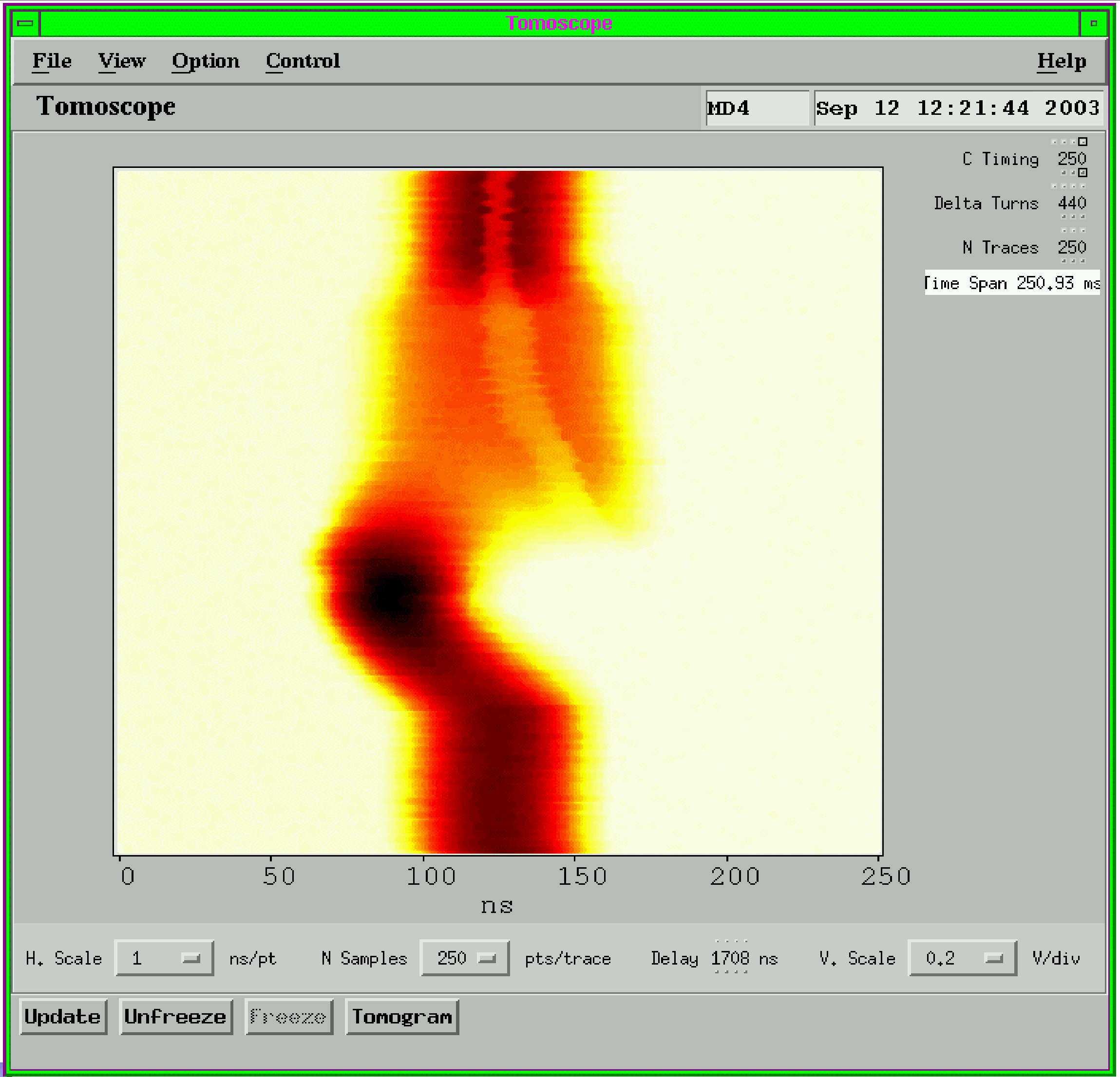
Test experiment in CERN PS



Merging of circulating bunch with empty phase space.

Longitudinal emittances are conserved

Negligible blow-up

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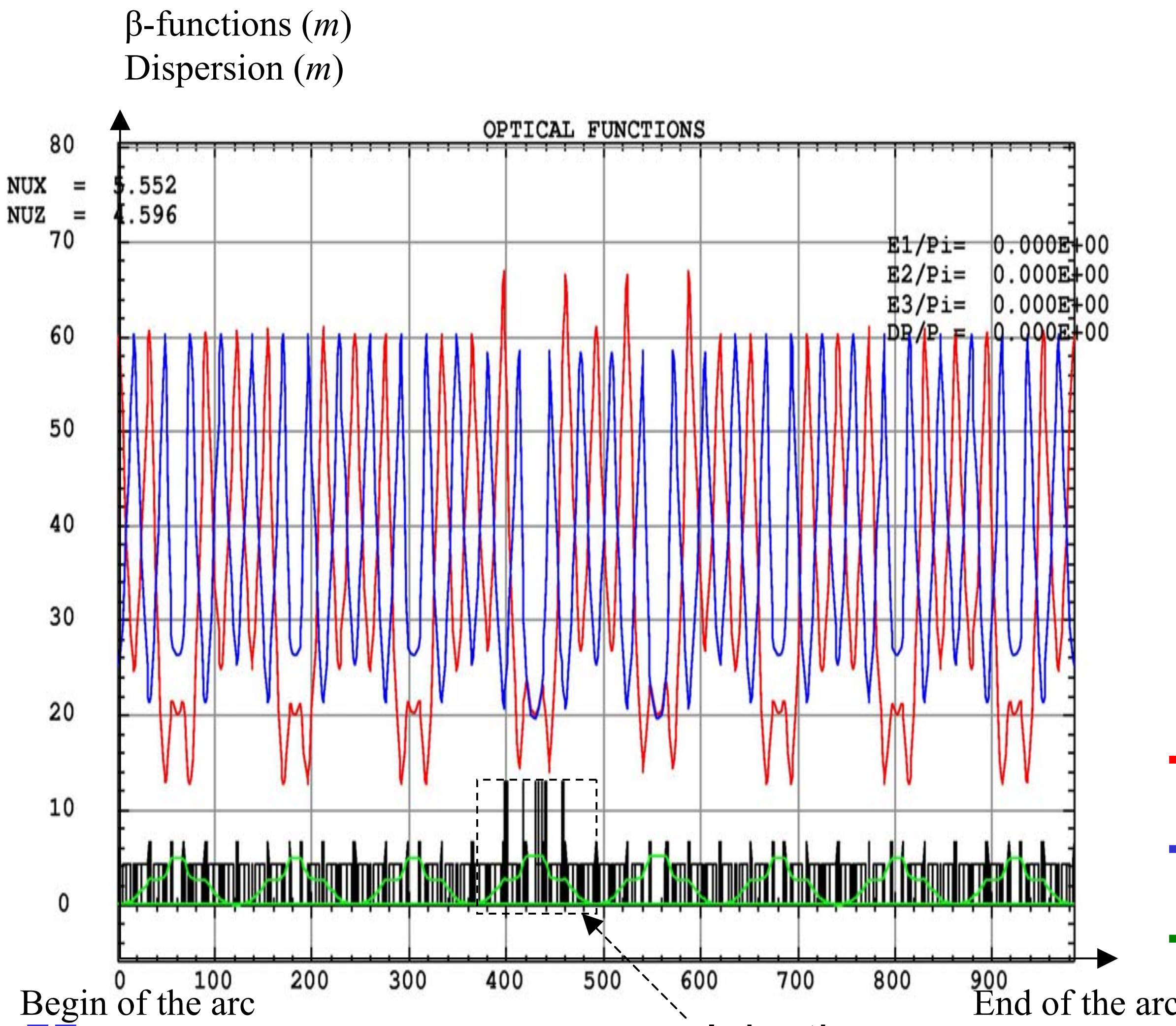
Decay ring arc lattice design

A. Chance, CEA-Saclay (F)



FODO structure

Central cells detuned for injection

Arc length ~984m

Bending 3.9 T, ~480 m l_{eff}

5 quadrupole families

— Horizontal β_x

— Vertical β_y

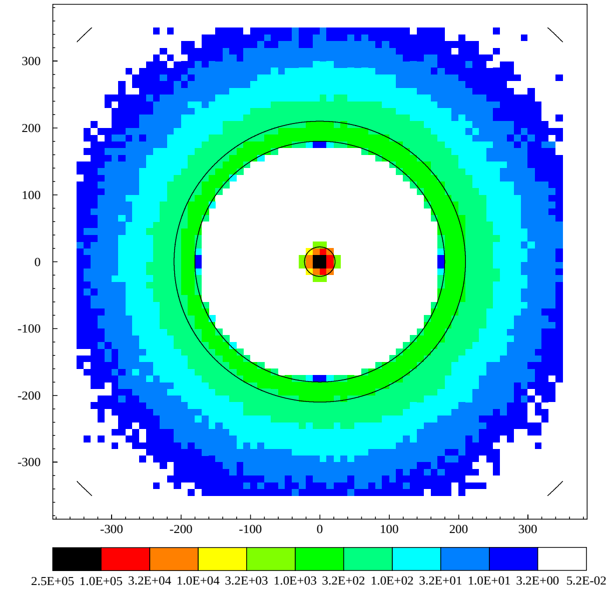
— Horizontal Dispersion D_x

slide from M. Benedikt

Radiation protection - decay losses

- Losses during acceleration
  - Full FLUKA simulations in progress for all stages (M. Magistris and M. Silari, *Parameters of radiological interest for a beta-beam decay ring*, TIS-2003-017-RP-TN)

- Preliminary results:
  - Manageable in low energy part
  - PS heavily activated (1s flat bottom)
    - Collimation? New machine?
  - SPS ok.
  - Decay ring losses:
    - Tritium and Sodium production in rock well below national limits
    - Reasonable requirements for tunnel wall thickness to enable decommissioning of the tunnel and fixation of Tritium and Sodium



FLUKA simulated losses in surrounding rock (no public health implications)

slide from M. Benedikt

Future R&D

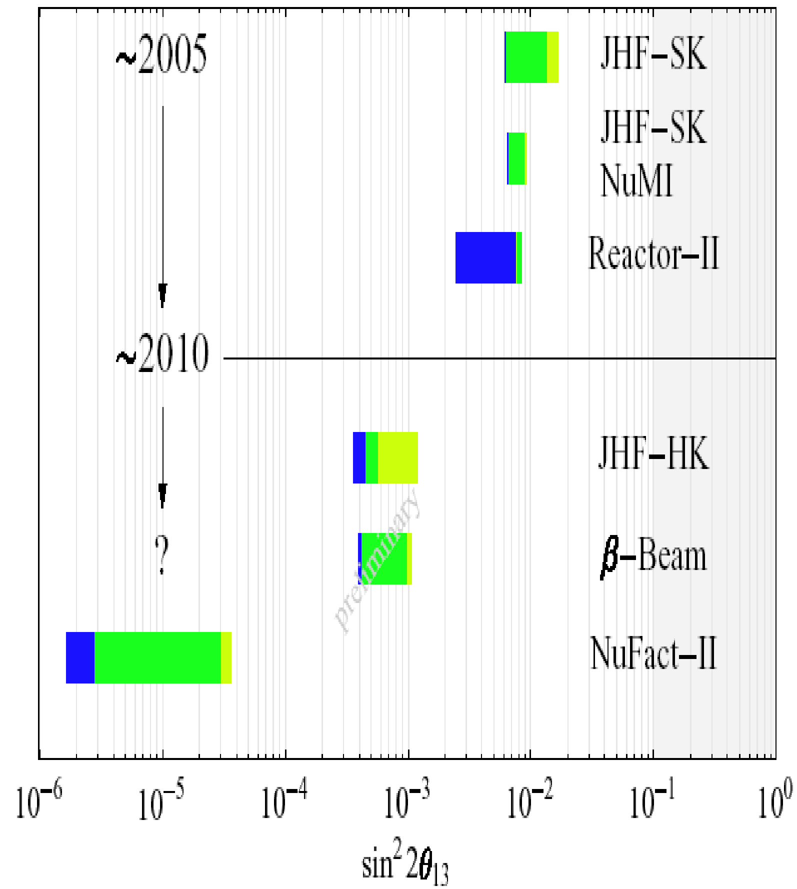
- Future beta-beam R&D together with EURISOL project
- Design Study in the 6th Framework Programme of the EU

- The EURISOL Project
  - Design of an ISOL type (nuclear physics) facility
  - Performance three orders of magnitude above existing facilities
  - A first feasibility / conceptual design study was done within FP5
  - Strong synergies with the beta-beam especially low energy part:
    - Ion production (proton driver, high power targets)
    - Beam preparation (cleaning, ionization, bunching)
    - First stage acceleration (post accelerator ~100 MeV/u)
    - Radiation protection and safety issues

slide from M. Benedikt

Physics Reach

- Physics reach of SPS-> Frejus beta-beam similar to super-beam.
  - May reduce systematics by combining the two
- Energy resolution in detector washed out by Fermi motion due to low energy.
  - Go to higher energies!



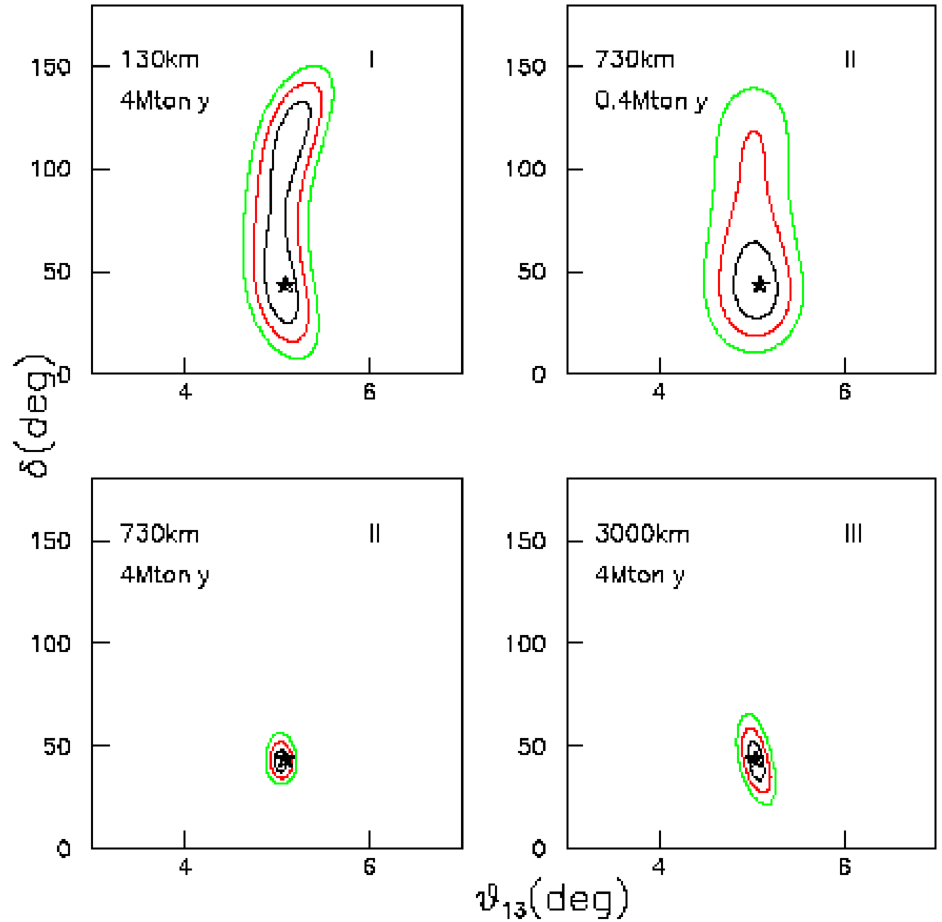
Higher energy beta-beams

- 'Original' energy scale was set by SPS.
- Potential of higher energies studied by Burguet-Castell *et al*
  - *Neutrino oscillation physics with a higher gamma beta-beam*, Nucl.Phys.B695:217-240,2004.
- Three scenarios studied:
  - *γ(He)=60, γ(Ne)=100, L=130km (CERN/SPS-Frejus)*
  - *γ(He)=350, γ(Ne)=580, L=732km (FNAL/Tev-Soudan)*
  - *γ(He)=1500, γ(Ne)=2500, L=3000km (CERN/LHC-Canary Islands)*

Higher energy beta-beams (2)

"Our results show that the intermediate option is spectacularly better than the low option previously considered, both in terms of the reach in CP violation as in the possibility to measure the neutrino mass hierarchy"

Nucl.Phys.B695:217-240,2004



Is it possible in practice?

Can it be done?

- Generic and fundamental questions will be addressed by the CERN/EU study
- Fermilab specific questions:
  - How much radioactive beam can the Tevatron accelerate without quenching due to decay losses?
    (N. Mokhov, answer expected early 2005)
  - Is it feasible to build a 1TeV (proton equivalent) decay ring with reasonable efficiency at the Fermilab site?
  - …

Decay losses during acceleration

values are for 6He2+ / 18Ne10+

Machine	Ramp time	Gamma	Est. Loss
Booster	0.03 s	3.3 / 5.4	2 % / 1 %
Main Injector	0.7 s	64 / 89	2 % / 1 %
Tevatron	17 s	349 / 581	10 % / 3 %

- Back-of-the-envelope estimate of decay losses in the acceleration chain seem manageable.
- About 1 10^{13} ions of either type per cycle should yield an average loss power of about 1 W/m in Tevatron.
- Loss power in other machines smaller.

Site constraints

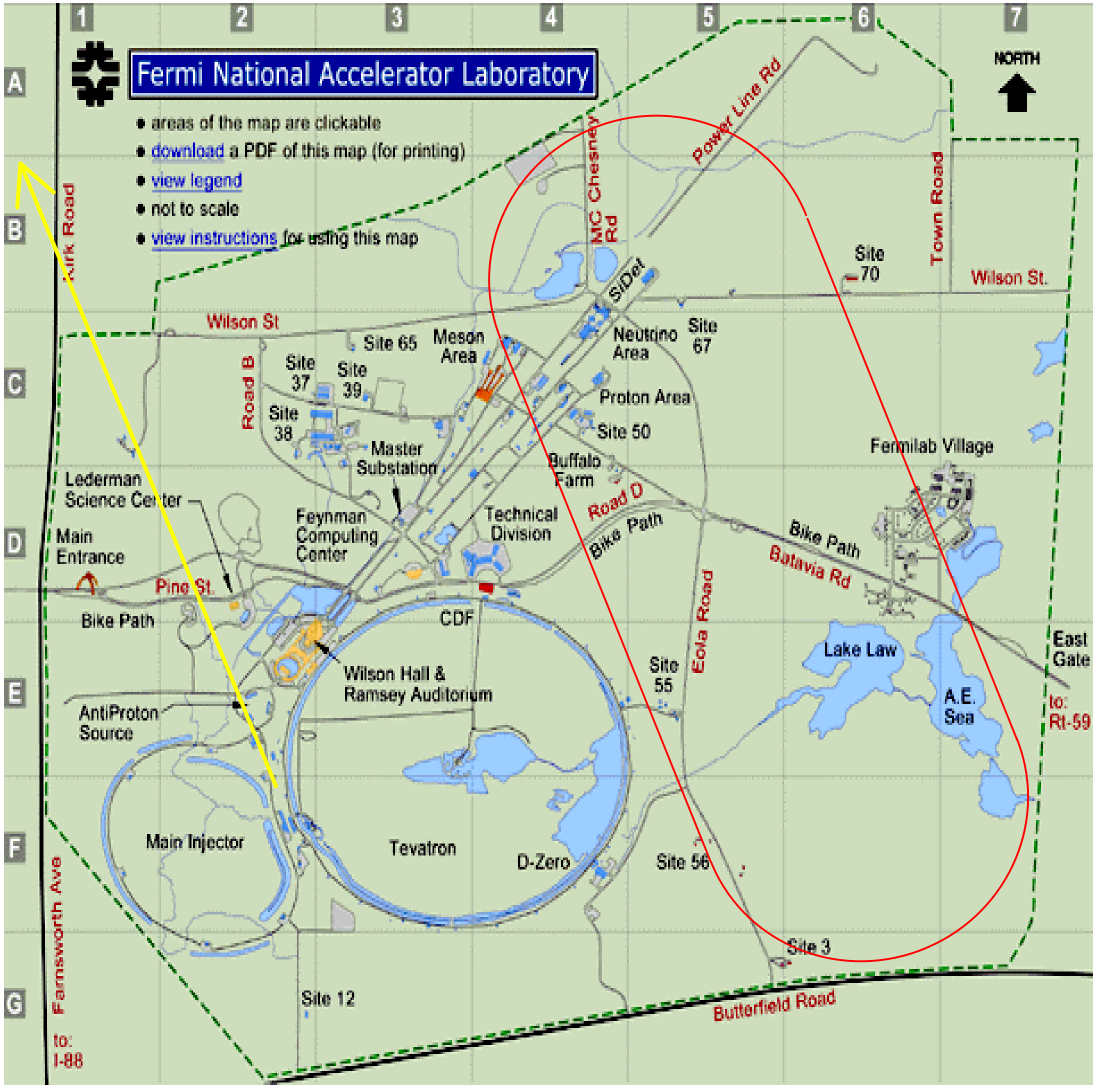
"Stretched Tevatron" aimed at Soudan

$B\rho$ = 3335 Tm
R = <u>1000 m</u> (75% 4.4T dipoles)
L_{SS}= ~3500

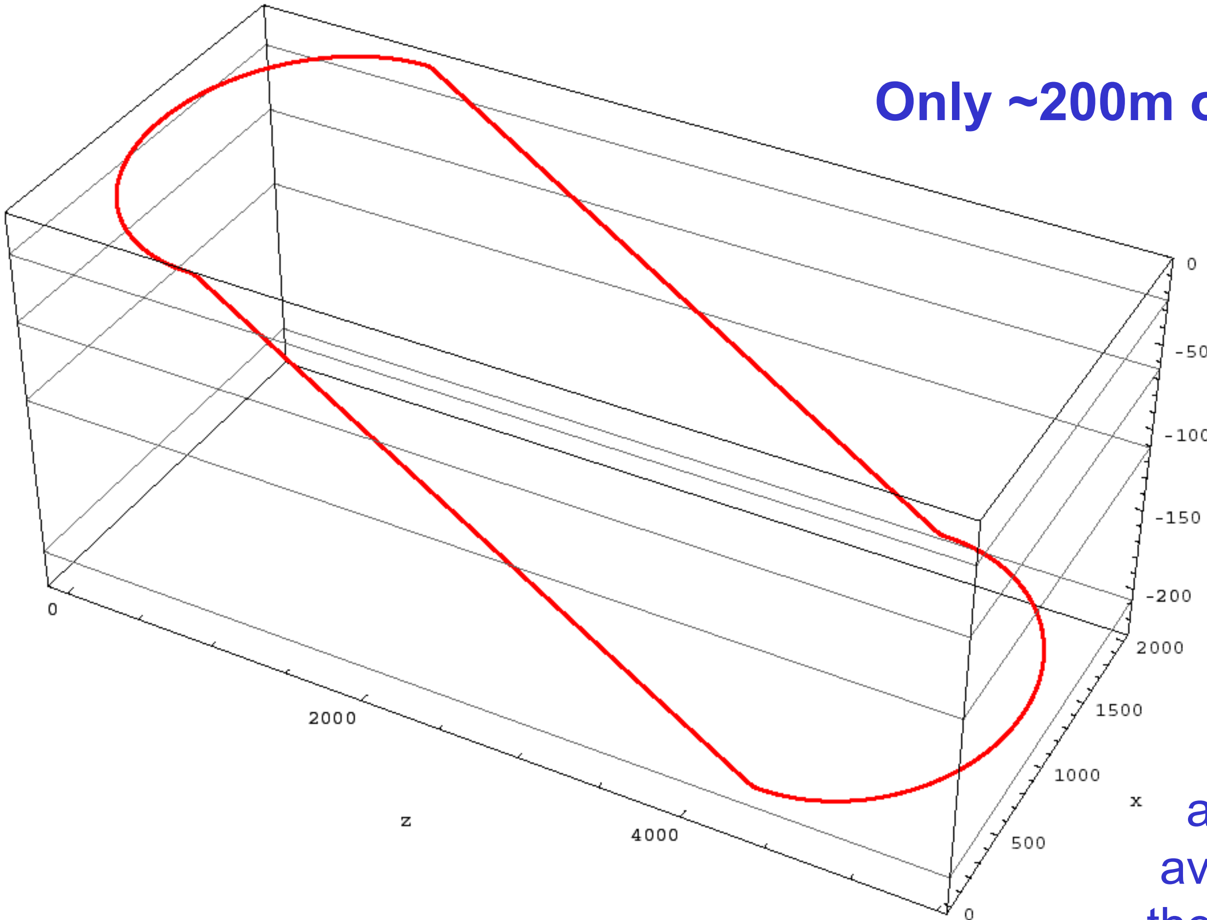
Total circumference: approximately 2 x Tevatron

320m elevation @ 58 mrad

26% of decays in SS



Geology constraints



Only ~200m of "good rock" available!

- Glacial till
- Silurian group (dolomite)
- Maquoketa group (shale)
- Galena/Platteville group (dolomite)
- Ancel group (sandstone)

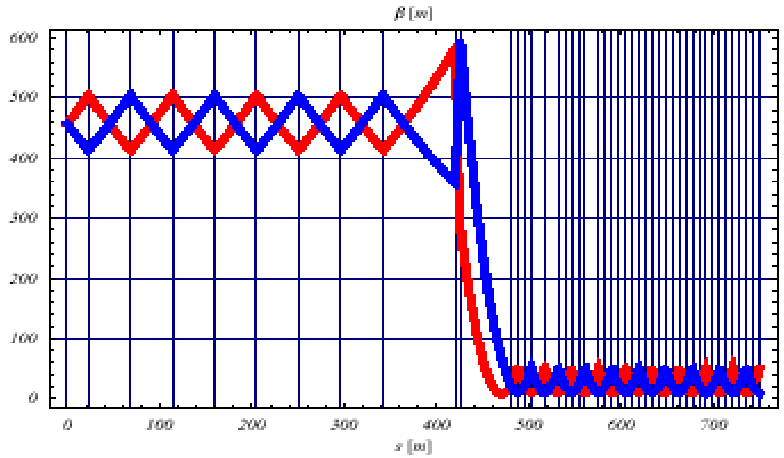
For a shallow angle (Soudan), a non-planar machine utilizes available depth better, due to the large bending radius.

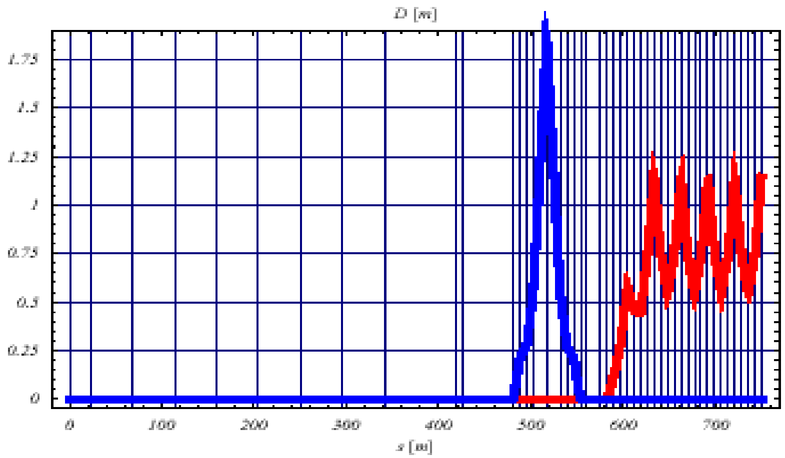
7% → 26% for Tevatron radius

NB. Vertical scale enhanced x10

Optics

- Toy optics design
  - Matching doublet
  - Dispersion free vertical bends
  - Horizontal dispersion suppressor
  - Tevatron B-fields and gradients
- Efficiency 25% -> 21%, could be increased with higher B-field (shorter arcs).





Ion intensities

- The comparative study assumed same number of decays/year for all three scenarios.
  - Same production rate requirements, but equilibrium stack will be correspondingly bigger, as particles live longer at higher gamma.
- Only $\frac{1}{4}$ of decays in the right direction
  - Need to reduce bending radius, or increase the ion production rate by x2 to compensate.
- May be issue with space charge
  - On the other hand, higher gamma option may not need as short and few bunches.

Conclusions

- If the physics case for Tevatron-energy beta beams is confirmed by further studies, it may be an interesting future option for Fermilab.
  - Decay loss limits of Tevatron will be known soon.
  - 1TeV decay ring of ~21% efficiency fits on site.
  - Efficiency may be improved with higher field magnets.
- Many more questions need to be addressed regarding the feasibility of the scheme, and the possibility of using existing Fermi machines for acceleration.
- A proton driver would be part of the scenario, albeit with a relatively modest power (~0.5 MW).